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Application of active and passive seismic methods for determining the shear wave velocity profile at hard rock sites in Eastern Canada

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ABSTRACT

It is often assumed that hard rock sites should exhibit no earthquake ground motion amplification, but in reality, some amplification occurs typically at higher frequencies due to weathered and fractured layers near the surface. According to seismic provisions in the National Building Code of Canada (NBCC), the subsurface ground conditions at a site is classified based on the time averaged shear wave velocity (V_S) of the upper 30 m (V_{S30}). Hard rock sites are classified as sites with a $V_{S30} \geq 1500$ m/s. Site characterization at seismograph stations of the Canadian National Seismograph Network (CNSN) is not robust or systematic. It is generally assumed that seismograph stations located on rock in Eastern Canada have a $V_{S30} \geq 1500$ m/s; *in situ* field measurements are not performed to verify this assumption. We aim to improve the site characterization at CNSN seismograph stations in Eastern Canada. We visited 25 seismograph sites and performed up to three seismic array measurements per site including compression-wave (Vp) refraction, multi-channel analysis of surface waves (MASW), and ambient vibration array (AVA) array methods as well as single sensor microtremor horizontal-to-vertical spectral ratio (MHVSR) measurements to constrain the site's seismic velocity depth profile. Overall, we find that the active-source seismic array methods (MASW and refraction) consistently provided velocity estimates whereas the passive-source seismic methods (AVA and MHVSR) provided limited velocity information. Single station MHVSR measurements at 11 of 23 tested sites showed either broadband high amplification (≥ 2) or sharp high frequency (≥ 10 Hz) peak(s). AVA measurements provided dispersion estimates over a narrow frequency band at 6 of 22 sites. MASW was successful in providing dispersion estimates at 21 of 23 sites. The Vp refraction technique was successful in estimating lower layer velocity at 20 out of 21 sites but depth profiles could not be resolved for all sites due to low sampling of the surficial layer.

Keywords: earthquake site assessment, earthquake site characterization, Vs30, site classification, hard rock

INTRODUCTION

Seismic waves propagating through soft sediments are amplified relative to stiffer ground [1] known as earthquake "site effects". Earthquake site characterization is important due to the established link between amplification and the shear-wave velocity (Vs) of subsurface strata [2]. Earthquake site classification according to Canadian seismic design guidelines in the 2015 building and bridge codes is based on the time averaged V_S of the upper 30m (Vs_{30}). V_{S30} is the sole site classification measure for rock sites whereas V_{S30}, undrained shear strength, or standard penetration testing blowcounts may be used to classify soil sites. Site-specific seismic hazard assessment, which incorporates a site's subsurface ground conditions in predicting earthquake ground motions is important for high-consequence facilities (e.g., nuclear power plants or hydro-electric dams) that are likely located on rock and designed for long (10,000 year) return periods.

Seismograph stations of the Canadian National Seismograph Network (CNSN) are typically placed on outcropping rock surfaces in Eastern Canada. Clusters of seismograph stations are placed in regions susceptible to earthquakes, e.g., Charlevoix, Quebec, which is historically subject to large earthquakes [3]. These stations provide few but valuable earthquake recordings to assess site response and high-frequency ground motion attenuation (seismic kappa) at rock sites in Canada. It is generally assumed that seismograph stations located on outcropping rock in Eastern Canada are located on "hard rock" ($Vs_{30} \geq 1500$ m/s); *in situ* field measurements are not performed to verify this assumption. Robustness in the site evaluation (assignment of V_{S30}) at rock sites across Canada is therefore poor. The acquisition of *in situ* geophysical measurements at seismograph stations is important to characterize subsurface material properties to model earthquake ground motions. There have been previous efforts to provide velocity depth profiling via V_S refraction testing at 11 Quebec and Ontario seismograph stations [4] to predict theoretical site amplification functions. Beresnev and Atkinson [4] show that the theoretical transfer functions exhibit low amplification (< 2) for these "hard rock" sites with an average rock V_S of ~2600 m/s. Earthquake horizontal-to-vertical spectral ratio (EHVSR) analysis across "hard rock" seismograph stations in Canada [5] confirm low amplification (< 2) that increases (≥ 2) at higher frequencies (> 10 Hz) but is limited to 20 Hz maximum due to the CNSN seismograph 40-Hz sampling rate. Braganza et al. [6] performed MHVSR testing at 10 Ontario seismograph stations and demonstrated similar site amplification compared to EHVSRs, i.e., MHVSRs accurately predict earthquake site amplification at the linear soil response or weak-motion level. Braganza et al. [7] developed site amplification models for organic fill, sand and clay, and rock sites, where the rock amplification response is a flat, low amplitude (~1) at low frequencies (< 10) with varying amplification at higher frequencies (> 10). Farrugia et al. [8] was the first to apply both MHVSR and AVA testing at Canadian seismograph stations in Alberta. Similar to Braganza et al. [6,7], Farrugia et al. [8,9] demonstrate consistent MHVSR and EHVSR site amplification and develop site amplification models for muskeg, sand and clay, and rock sites. The Alberta rock amplification model is similar to that of Ontario in having low amplification across low frequency bandwidths (<10 Hz) with some variability in the amplification occurring at higher frequencies (> 10 Hz).

Active- and passive-source seismic (surface wave and microtremor) methods are under investigation for their applicability and use in measuring V_{S30} at rock sites worldwide (i.e. [10-14]). There have been few case studies of surface wave dispersion and ambient vibration methods for earthquake site characterization (velocity profiling) at rock sites [10-13]. Site characterization using passive seismic techniques at rock or stiff soil sites have been subjective due to the lack of a large impedance contrast at these sites to develop surface waves with a detectable amplitude in the ambient wave field [12] but there has been success. The InterPacific project [10] blind test comparison of non-invasive and invasive V_S profiling methods included a Cretaceous limestone rock site. Both active and passive techniques were worthwhile in providing dispersion estimates of the rock velocity. Hollender et al. [11] applied these same techniques at rock sites in France with success from both active and passive methods. In reality, weathering and jointing or fracturing of the rock (to unknown depths) and/or the presence of thin overlying soils during seismic testing promotes generation of surface waves and ambient vibrations.

In this study, multiple non-invasive seismic methods are performed at 25 seismograph stations in Eastern Canada (Figure 1) to examine the applicability of these methods for Canadian rock sites and contribute to the limited body of knowledge in earthquake site characterization and classification at rock sites worldwide. Stations are typically separated by 50-100's km throughout Ontario, Quebec, New Brunswick and Nova Scotia with seismometers clustered near Ottawa and Charlevoix, Quebec where seismic activity is higher. Active-source methods include compression wave (Vp) refraction and multi-channel analysis of surface waves (MASW) performed using a Geode seismograph and up to 24 4.5-Hz vertical-component geophones. Passive-source methods include ambient vibration array (AVA) and microtremor horizontal-to-vertical spectral ratios (MHVSR's) performed using up to 5 tri-axial Tromino® seismometers. Each site was visited by a two-student field crew for a duration of 2-3 hours during two field campaigns in summer and fall of 2017. This paper summarizes the methods used, their success in application, and our preliminary earthquake site assessment at each site.

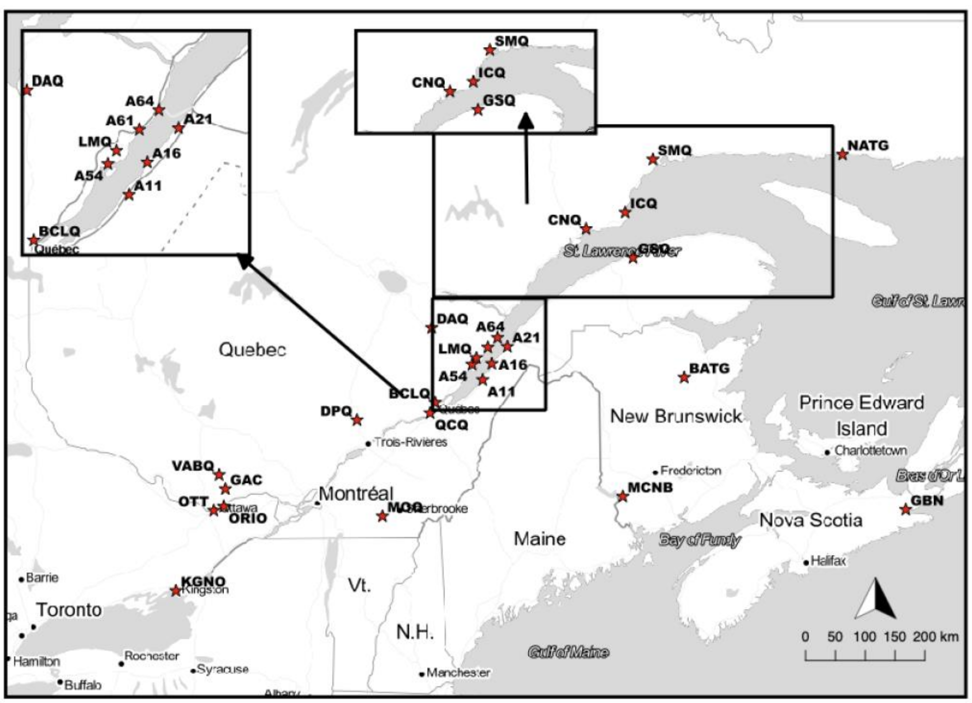

Figure 1. Map of CNSN seismic station locations visited during the 2017 field campaign with zoomed in areas of interest

NON-INVASIVE ACTIVE AND PASSIVE SEISMIC ARRAY METHODS

Background and Field Acquisition

Surface waves are dispersive in nature meaning that different frequencies (and wavelengths) travel with different velocities. High frequency surface waves travel slower than low frequency waves due to travelling in the shallow low velocity material near surface compared to high velocity material at depth. A general assumption is that surface waves dominate the microtremor wavefield [15]. Rayleigh wave velocity is similar to that of Vs, related through Poisson's ratio, and measured surface wave dispersion can be used to obtain a Vs profile [16]. MASW and AVA are efficient and cost-effective surface wave techniques to acquire V_S profiles through dispersion analysis. Passive AVA testing provides low-frequency dispersion estimates whereas active MASW testing typically provides higher frequency dispersion estimates. A final site-specific dispersion curve is extracted over a wide frequency band by combining dispersion estimates from both methods.

In MASW testing [17] Rayleigh surface waves are actively generated by a vertical-impact source (i.e., sledgehammer) and are measured at a distance by a linear array of vertical-component receivers. Linear arrays are typically used with multiple source and receiver offsets to vary spatial resolution and depth of penetration. Dispersion data is then generated through frequency-wavenumber (f-k) processing. Dispersion estimates are picked from processed dispersion (Rayleigh wave phase velocity vs. frequency) histograms which are then inverted for a 1D earth model which can be used to estimate V_{S30}. MASW data was collected using a Geode seismograph with up to 24 4.5-Hz vertical geophones. Receiver spacing of 0.5, 1, and 3 m are used with source offsets of 5 and 15 m at each end of the geophone line. The seismic source is an 8 lb sledgehammer struck vertically on a steel plate; multiple hammer impacts are recorded for consistency among shots.

Active-source Vp refraction methods take advantage of the phenomenon that a seismic wave will refract at an impedance boundary. The generated seismic wave (ray) refracts along the interface (head wave) and refracts back at the critical angle to the geophones. Travel time analysis is used to extract velocities given the source and receiver offsets and times of first arrivals of direct and refracted waves. Cross-sectional 2D depth profiling is fulfilled if source locations are at both ends of the line (i.e., forward and backward shots) to detect if traveltimes are changed and therefore indicate dipping of the subsurface strata. Vp refraction data is collected at the CNSN stations using the same equipment and MASW array setups.

AVA testing involves multiple geophones positioned in a 2D array to record ambient vibrations from multiple azimuths. AVA recordings are processed using the modified spatial autocorrelation (MSPAC) technique [18]. MSPAC processing is a modification of the spatial autocorrelation method (SPAC; [19]) which assumes ambient vibrations are a temporal and spatial stochastic process to evaluate the coherency spectra between pairs of sensors in arrays [20]. MSPAC provides a modification for imperfect array symmetry using azimuthal averaging over narrow station-pair distance intervals. Dispersion estimates are picked from SPAC curves and combined with MASW dispersion estimates which can be inverted for a 1D earth model (i.e., V_S profile). AVA data are collected using up to 5 three-component Trominos® with varying array spacings up to 20 m. The geometry of the arrays was typically performed with an X-shape geometry with a central sensor. Varying array sizes were used throughout the survey to access different frequency bandwidths of dispersion information. MHVSR's were generated from AVA data as well as single station Tromino® measurements beside the seismograph station on concrete or the residing rock or soil.

Data Conditioning

During two field campaigns in 2017, 25 seismograph stations across Eastern Canada were visited (Figure 1; Table 1) to apply *in situ* seismic methods. The same methods are attempted at all seismograph stations including refraction, MASW and AVA for velocity profiling and MHVSR for site amplification. Our aim is to measure the rock velocity with depth and thereby V_{S30} at these seismic stations using non-invasive seismic methods. A parallel study is underway [21] to update seismic kappa at these stations using a decade of additional earthquake recordings since [22]. In summary, a compromise of the above described methods are performed at the 25 CNSN stations due to limited access and space (see Table 1).

Data processing was performed by the Geopsy toolbox (version 20170109) freely available online [23]. The simultaneous vertical-component AVA recordings are processed using MSPAC analysis to retrieve dispersion estimates. MHVSRs are calculated using single station recordings which are segmented into 30 second time windows with bad windows removed. MASW data are converted from the Geode SEG-Y data format to Miniseed using a Python routine to import into a Geopsy database for fk processing to retrieve dispersion estimates. Time-windows of 1-sec are clipped to extract each shot's waveform from the 12-24 vertical-component continuous linear-array recordings. Similar shots are stacked together and are normalized by their maximum beam power. P-wave refraction was processed using travel-time analysis by picking direct and refracted wave first arrivals to acquire layer velocities and layer thicknesses. Depth is calculated for some sites via Eq. (1) assuming a simple, flat 2-layer case where t represents the first arrival of the refracted wave, θ_{12} is the critical angle between the top two layers, and v_1 is the velocity of the topmost layer,

$$z = \frac{t_1 * v_1}{2\cos(\theta_{12})}. \qquad (1)$$

DIVERSITY IN RESULTS

Although the same methods are applied at each site, data quality ranged amongst sites based on their site characteristics and ambient wavefield. Overall active-source refraction and MASW methods are more successful in consistently providing velocity and dispersion estimates, respectively. When thin soils are present at surface, MASW typically only provides dispersion estimates of this surficial soil whereas refraction consistently provides 2-3-layer velocity estimates (with lowermost layers interpreted as rock velocity). The passive-source AVA method is less successful in consistently providing velocity estimates; in very few cases are dispersion estimates obtained. And if obtained, only over a very narrow frequency interval. Only the passive-source MHVSR method is performed at all sites (not constrained by space limitations) and verifies that rock sites demonstrate little to no amplification or high-frequency peaks.

MHVSR site amplification spectrum

Single Tromino® MHVSR measurements are performed immediately beside, or on the same concrete base as, the CNSN seismograph. Details of the time-averaged MHVSR results are summarized in Table 1. The MHVSR's show relatively "flat" low amplification (< 2) for 10 of 25 stations (Figure 3a). A flat low amplification spectrum confirms very stiff or hard rock site conditions but cannot be inverted to obtain the rock velocity. At the other 7 stations, the MHVSR amplification is slightly increased at lower frequencies combined with a high frequency (>10 Hz) peak (Figure 3b). The high frequency peak can be inverted with dispersion estimates from MASW or AVA to constrain the depth of surficial soils and the impedance contrast that gives rise to the measured MHVSR peak, i.e., there is some measured constraint on the underlying rock velocity. The increased broadband amplification (> 2) results from an increased impedance contrast overall from reduction in velocity and/or density towards surface. The interpretation is these rock sites (Figure 3b) are generally softer, with increased weathering, or jointing and fracturing, and/or increased topography compared to the stations in Figure 3a.

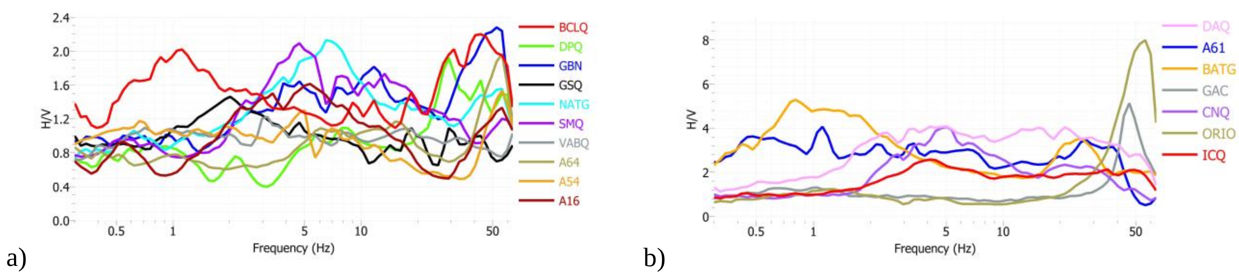

Figure 3. Time-averaged MHVSR amplification spectra from single-sensor measurements performed beside the CNSN seismograph for sites with (a) relatively 'flat' (< 2) amplification and.(b) a clear broad or sharp MHVSR peak.

AVA

MSPAC dispersion results from AVA recordings varied with some success (8 of 22 sites) in acquiring dispersion estimates (Figure 4a) but for the majority of sites, no dispersion estimates are obtained (Figure 4b). Potential dispersion estimates of the rock velocity are observed at 5 of 22 sites with dispersion estimates retrieved for 6 of the 22 sites.

MASW

MASW testing consistently provided dispersion estimates but not necessarily of the underlying rock. Typically, low velocities at high frequencies (surficial soils) and the rapid increase in phase velocities at lower frequencies (transition to rock) is observed. For 5 of 23 stations, the phase velocities plateau at low frequencies and provide a measure of rock velocity (Figure 5a). Some sites only capture a low velocity (soil) layering and do not penetrate deep enough to provide the subsurface rock velocity (Figure 5b). MASW dispersion estimates (Table 1) obtained at very high frequencies indicate that rock is very close to the surface. Another observed site characteristic in few cases is the evidence of a dipping interface as the dispersion estimates vary along the 24-geophone array line.

Refraction

Vp refraction testing successfully provides measured rock velocity at most sites. Extracting both reliable direct and refracted wave arrivals is required to determine the site's velocity depth profile. Station CNQ was the only station where wave arrivals could not be picked. 5 stations showed velocity at depth rather than the surficial soil leading to the inability to create the site's velocity depth profile. Due to performing seismic-source hammer shots at the front and back of the geophone line, we could determine 2D velocity estimations along the survey line. 7 sites provided consistent velocity estimates from the forward and back shots indicative of flat layering. 8 sites showed that forward and back refraction-travel-time analysis would provide additional wave arrival picks (additional layer) or highly variable depths for the same layering, i.e., dipping layers. By observing the refracted wave travel times and apparent velocities, a 2D model is built to geometrically determine the true velocity of the dipping layer. The lowest layer (rock) Vp is useful in constraining the Vp parameter bounds and thereby V_S through Poisson's ratio in dispersion inversions for that site.

Table 1. List of CNSN seismograph stations visited, their site conditions, and details of the seismic methods performed. SS corresponds to single station MHVSR measurements performed beside the CNSN seismograph. P corresponds to passive AVA measurements, and A corresponds to active MASW and Vp refraction measurements. Active measurements are performed with Trominos® where space is limited and is noted as $A_{Tromino}$.

Station and coordinates	Measurements performed and their site conditions	Array Spacing	MHVSR	Dispersion estimate bandwidth (Hz)
A11 Lat: 47.2431 ^{0}N, Long: -70.1968 ^{0}E	SS: Rock	N/A	N/A – Wind effects; station on a hill	N/A
A16 Lat:47.4706 ^{0}N, Long: -70.0064 ^{0}E	SS: Thin soil over rock P: Soil/gravel A: Soil/grass cover beside rock	P: 3, 6, 9, and 12 m A: 0.5 m	Flat, low A	A: 22-48
A21 Lat:47.7036 ^{0}N, Long:-69.6897 ^{0}E	SS: Soil/rock mix	N/A	N/A – Wind effects; station on a hill	N/A
A54 Lat:47.4567 ^{0}N, Long:-70.4125 ^{0}E	SS, P, and A: Soil	P: 3,6, and 9 m A: 0.5 m	Flat, low A	A: 20-120
A61 Lat:47.6936 ^{0}N, Long:-70.0913 ^{0}E	SS: Soil P: Gravel A: Soil/Gravel	P: 5, 10, and 15 m A: 1 and 3 m	f_{peak} at 25 Hz, high A across all f	A: 25-70
A64 Lat:47.8264 ^{0}N, Long:-69.8922 ^{0}E	SS: Concrete pad P: Rock A: Thin layer over rock	P: 3, 6, 9, and 12 m A: 0.5 m	Flat, low A	P: 25-35 A: 89-135
BATG Lat:47.2767 ^{0}N, Long:-66.0599 ^{0}E	SS: Soil P: Gravel/soil mix A: Gravel	P: 3, 6, 9, 12, and 15 m A: 1 and 2 m	f_{peak} at 0.7 and 25 Hz	A: 15-100
BCLQ Lat:49.926 ^{0}N, Long: -71.173 ^{0}E	SS: Rock P and A: Soil	P: 3, 6, 9, and 12 m A: 1 m	f_{peak} at 1.5 Hz and 45 Hz	A: 30-75
CNQ Lat:49.302 ^{0}N, Long: -68.0746 ^{0}E	SS: Concrete P and A: Soil over rock	P: 3, 6, 9, and 12 m A: 0.5 m	f_{peak} at 5 Hz	N/A
DAQ Lat:47.9627 ^{0}N, Long: -71.2437 ^{0}E	SS: Rock P: Rock and Soil A: Soil	P_{rock}: 2, 4, and 6 m P_{soil}: 4, 8, and 12 m A: 1 m	Flat, high A	A: 12-80
DPQ Lat:46.6804 ^{0}N, Long:-72.7774 ^{0}E	SS: Rock P: Thin soil over rock A: Soil	P: 3, 6, and 9 m A: 0.5 and 1 m	Flat, low A	A: 15-85
GAC Lat:45.7033 ^{0}N, Long:-75.4783 ^{0}E	SS and $A_{Tromino}$: Soil	A: 1 and 3 m	f_{peak} at 20-40 Hz	A:170-480
GBN Lat:45.4077 ^{0}N, Long:-61.5128 ^{0}E	SS: Rock P: Stiff soil A: Mix of soil/gravel/sand	P: 3, 6, 9, and 12 m A: 0.5 and 1 m	f_{peak} at 50 Hz	A: 20-125
GSQ Lat:48.9142 ^{0}N, Long:-67.1106 ^{0}E	SS: Soil/gravel P: Soil/gravel A: Soil	P: 3, 6, 9, and 12 m A: 1 m	Flat, low A	A: 10-115
ICQ Lat:49.5217 ^{0}N, Long:-67.2719 ^{0}E	SS: Rock P: Rock and soil $A_{Tromino}$: Sand/soil	P_{rock}: 2 and 4 m P_{soil}: 5, 10, and 15 m A: 1, 3, and 5 m	f_{peak} at 5 Hz	P: 15-25 A: 60-215
KGNO Lat:44.2272 ^{0}N, Long:-76.4934 ^{0}E	P: Grass/soil A: Soil	P: 3, 6, and 12 m A: 1 m	N/A – No Access	P: 21-35 A: 50-100

LMQ Lat:47.5485 ^{0}N, Long:-70.3258 ^{0}E	SS: Concrete P: Gravel A: Mix of soil, and gravel	P: 3, 6, 9, and 12 m A: 1 and 2 m	N/A – external noise	A: 10-90
MCNB Lat:45.59582 ^{0}N, Long:-67.31982 ^{0}E	P and A: Soil	P: 5, 10, and 15 m A: 1 and 1.5 m	N/A – No access	A: 45-125
MOQ Lat:45.312 ^{0}N, Long:-72.2541 ^{0}E	SS: Concrete P: Gravel A: Soil	P: 3, 6, and 9 m A: 1 m	N/A – external noise	N/A
NATG Lat:50.2872 ^{0}N, Long:-62.8102 ^{0}E	SS: Rock P: Rock A: Soil	P: 5, 10, and 15 m A: 0.5 and 1 m	f_{peak} at 7 Hz	N/A
ORIO Lat:45.4515 ^{0}N, Long:-75.511 ^{0}E	SS, P, and A: Soil	P: 3, 6, 9, and 12 m A: 1 m	f_{peak} at 55 Hz	P: 10-30 A: 30-215
OTT Lat:45.3942 ^{0}N, Long:-75.7167 ^{0}E	SS: Concrete pad P and A: Soil	P: 5, 10, and 15 m A: 1 and 3 m	N/A – external noise	P: 5-20 A: 20-120
QCQ Lat:46.7791 ^{0}N, Long:-71.276 ^{0}E	SS: Concrete pad P and A: Soil	P: 10, 15, and 20 m A: 1 and 3 m	N/A – external noise	P: 10-25 A: 30-170
SMQ Lat:50.2225 ^{0}N, Long:-66.7025 ^{0}E	SS: Concrete pad P: Rock $A_{Tromino}$: Gravel	P: 3, 6, and 9 m A: 1 and 3 m	f_{peak} at 5 Hz	N/A
VABQ Lat:45.9047 ^{0}N, Long:-75.6079 ^{0}E	SS: Soil P and A: Soil	P: 5, 10, and 15 m A: 1 m	Flat, low A	N/A

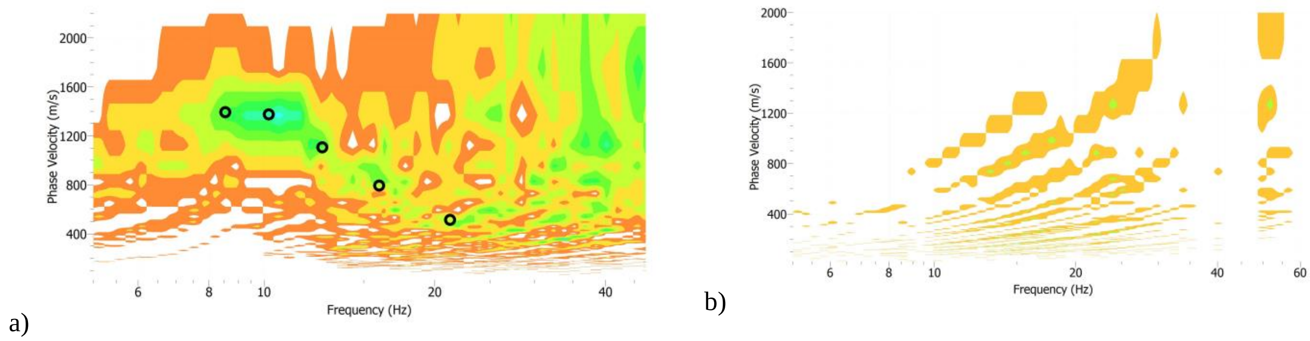

Figure 4. Two cases of MSPAC dispersion histograms from AVA recordings at station (a) station OTT with retrieved dispersion estimates (open circles) and (b) station NATG showing no success in measuring dispersion.

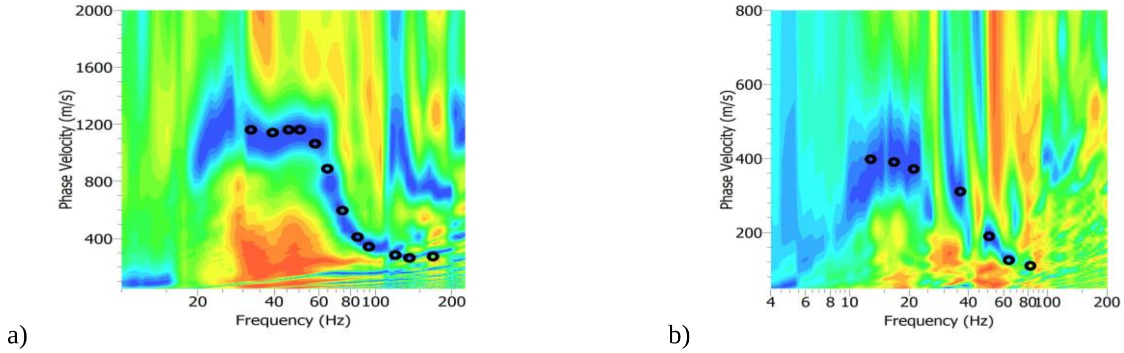

Figure 5. MASW dispersion histogram for (a) station QCQ with observed phase velocities (> 1000 m/s) of underlying rock and (b) station DAQ with observed phase velocities (< 400 m/s) of shallow sediments.

Dispersion Estimates

The retrieved dispersion estimates from AVA and MASW testing are summarized here for all sites (Figure 6). The frequency bandwidth of the active- and passive-source dispersion methods are reported in Table 1. The solid black line in Figure 6 indicates an estimate of V_{S30} from the phase velocity of a 40-m wavelength Rayleigh wave [24] and is estimated from Eq. (2).

$$Vs30 = 1.045 * Vr40 \; . \qquad (2)$$

Figure 6 shows that measured dispersion estimates at most CNSN seismograph stations are high, corresponding to site class B. Only at 2 stations are measured phase velocities high enough to confirm hard rock (class A) site conditions. Based on the measured dispersion estimates, nearly all CNSN seismograph stations are classified as “soft rock” instead of “hard rock”.

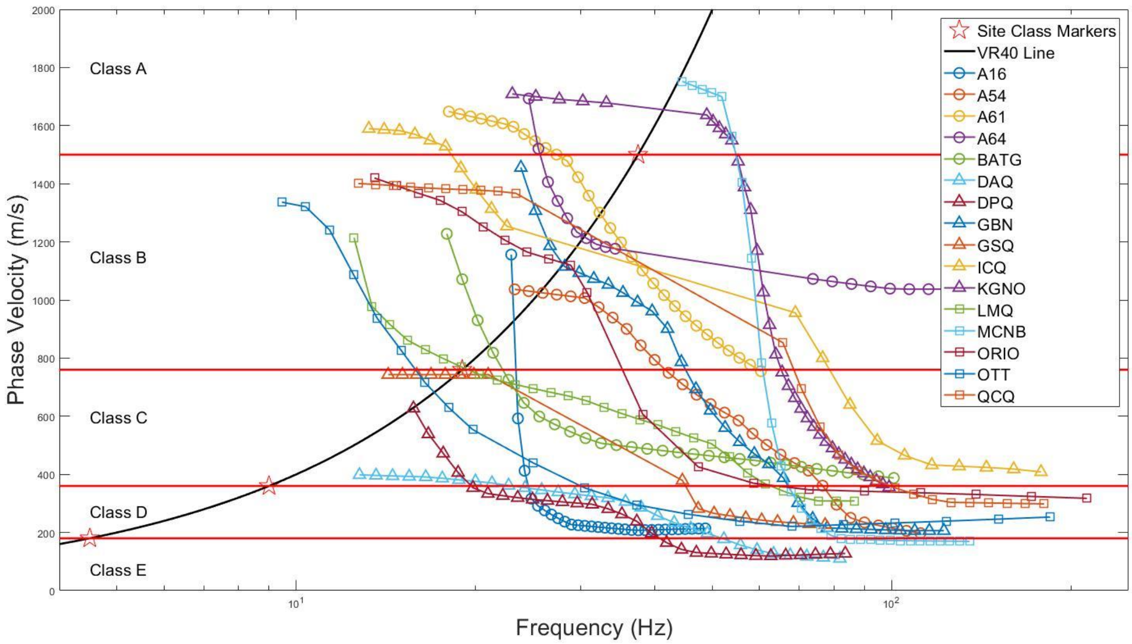

Figure 6. Dispersion estimates from active- and passive-source array methods. Solid black line shows Vr40 with converted Vs30-to-Vr40 site class boundaries denoted as stars and labelled.

CONCLUSIONS

We perform multiple non-invasive seismic methods and assess their success in site characterization at 25 CNSN rock stations across Eastern Canada. MHVSR’s beside the station assisted in confirming harder or softer rock amplification spectra and narrowing the frequency bandwidth in dispersion picking. AVA testing had the lowest success rate, but proved most useful in measuring phase velocity of underlying rock. MASW was successful in providing wider-frequency dispersion trends at sites but with a varying amount of success in retrieving velocity estimates of the underlying rock. Vp refraction was very useful and successful in providing Vp of lowermost rock layers and in some cases, the upper soil layer(s). Each method provides unique site information and therefore value in the site assessment. More empirical *in situ* studies need to be performed at rock sites to validate a robust method for their site characterization. More sensors, a circular array geometry, and larger spacings were shown to be successful in gaining dispersion characteristics at rock sites (i.e. [10]), although we note larger spacings are typically not a viable option at CNSN stations. In future, we recommend S-wave refraction be performed which is known to provide rock V_S (e.g. [12]).

Our dispersion estimates demonstrate that CNSN rock sites primarily correspond to site class B, in disagreement with the assumed hard rock class A categorization. We will invert the dispersion estimates to obtain V_S profiles to verify the site class assignment of each site. This study emphasizes the need for *in situ* (seismic) testing to quantify underlying material stiffness and thereby provide accurate earthquake site characterization.

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